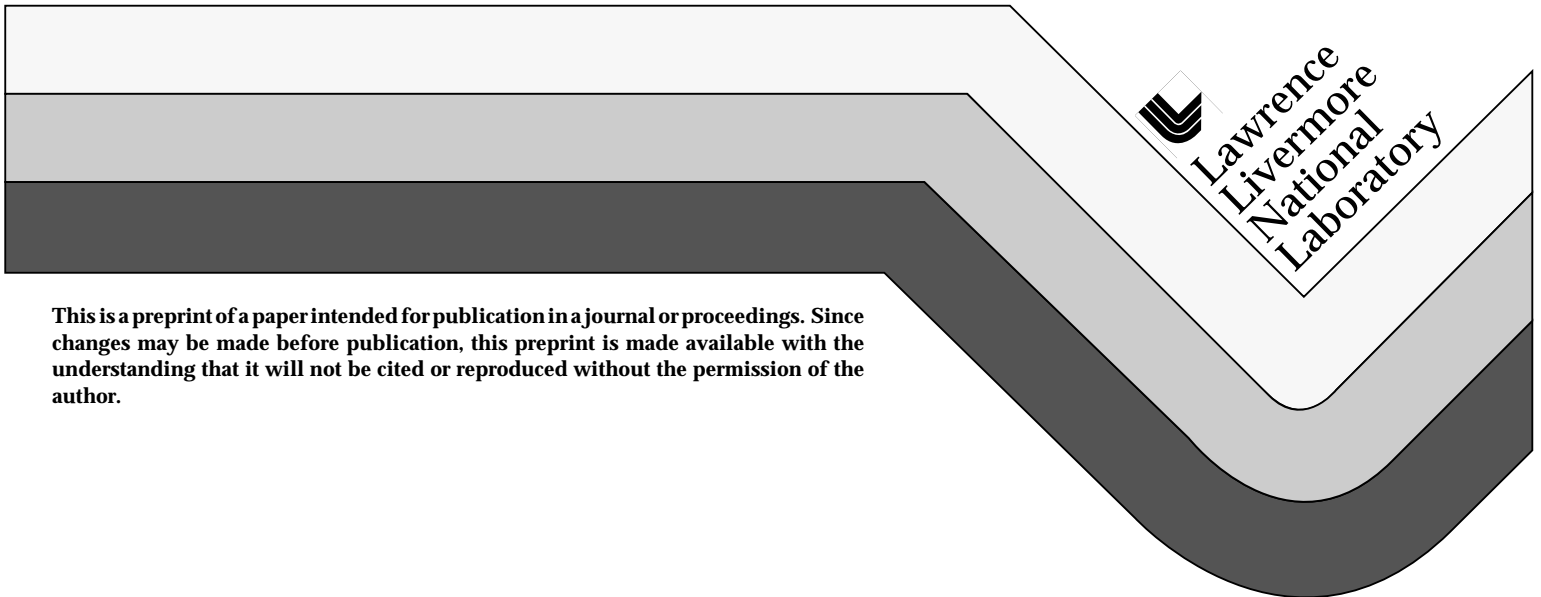


# Neutral Surface Layer Turbulence Over Complex Terrain

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## 1. INTRODUCTION

Accurate turbulence estimates are important input to atmospheric dispersion models since they characterize downwind dispersion and hence, potential pollutant concentrations. When only basic wind information is available, an atmospheric modeler must first estimate roughness length ( $z_o$ ) at the location of interest, ( $u^*$ ) from similarity theory using average wind speed ( $u$ ) and  $z_o$ , and finally apply experimentally-derived relationships to determine the turbulence intensities. Even when turbulence coefficients are measured, the turbulence profile must be estimated in the surface layer, using, for example, the power law recommended in a U.S. Environmental Protection Agency guidance document (EPA 1993).

The problem with widely used turbulence relationships is that they are based on a limited number of field experiments, conducted primarily over flat, smooth, and uniform (FSU) terrain. In addition, a summary of micrometeorological field studies listed by Pasquill (1974) indicates a lack of experimental data measured above 25 m AGL. Finally, many of the empirically-derived relationships are based on days or at most weeks of data and, therefore, they may not represent long-term averages. Consequently, the validity of widely-used turbulence relationships, especially over complex terrain where many sources of pollutants reside, is questionable.

High quality wind and turbulence data, measured on multi-level towers at Los Alamos National Laboratory (LANL) and at the Rocky Flats Environmental Technology Site (RF), are analyzed in this study. While the terrain at both sites is regionally complex,  $z_o$  is locally large at LANL and locally small at RF.

Previous studies at LANL (Bowen *et al.* 1983) and RF (Bowen and Pamp 1994) indicate that 15-minute averages of  $\sigma_\theta$  and  $\sigma_\phi$  decrease in a staircase fashion as the P-G stabilities increase from A to D at 10 m AGL. However,  $\sigma_\phi$  is surprisingly small at RF with  $\sigma_\theta/\sigma_\phi = 5$ . The  $\sigma_\theta/\sigma_\phi$  ratio at LANL approximates the widely used fraction of 2. Both studies revealed an increase of  $\sigma_\theta$ , and to a lesser extent,  $\sigma_\phi$ , as conditions became stable.

In this study, turbulent intensities and wind profiles are analyzed in eight direction sectors during near-neutral stability. “Local” and “regional” roughness lengths are calculated from wind speed profiles and from longitudinal turbulence intensities ( $\sigma_u$ ) at both sites. With “regional” roughness length, complex terrain features are in effect the roughness elements. Profiles of median, 15-minute averaged turbulence intensities  $\sigma_u, \sigma_v$ , and  $\sigma_w$  are calculated at both sites. Profiles of median  $\sigma_\theta$  and  $\sigma_\phi$  are also calculated using four mean values of regional  $z_o$  at both sites. Finally, differences between widely-used turbulence relationships and the relationships determined in this study, and their possible effect on model results, are discussed.

## 2. GEOGRAPHY AND SITING

The LANL is located 100 km north-northeast of Albuquerque and 40 km northwest of Santa Fe in north-central New Mexico. The laboratory is situated on the Pajarito Plateau on the eastern flanks of the Jemez Mountains. The plateau slopes downward to the east-southeast, covering a distance of more than 24 km from the base of the Jemez Mountains [approximately 2400 m above sea level (ASL)] to a location just above the Rio Grande River Valley (about 1900 m ASL). Numerous alternating “finger” mesas and canyons run along the plateau slope line. The canyons are 50 to 100 m deep and 100 to 200 m wide. The 92-m tower used in this study is located in a field that is in the midst of a ponderosa pine forest (see Fig. 1). The field, sloping 2.5° downwards to the east-southeast, is covered with grass (~0.5 m) and several bushes (1–2 m). The tower base elevation is 2265 m ASL. The surrounding pines (~20 m) especially affect the winds that approach the tower from the south as illustrated by the vista diagram in Fig. 2. The obstructed view averages 6° to 8° above the horizon towards the southeast through southwest and it peaks at 13° to the south of the tower base. The upwind fetch is relatively free of nearby obstructions east and west of the tower (i.e., along the field) except for the mountains 5 km to the west.

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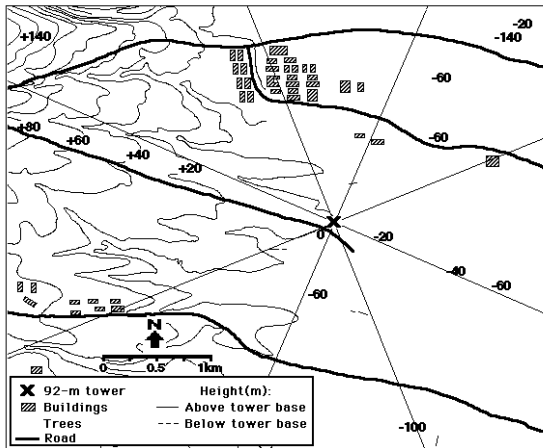


Figure 1. Contour map surrounding LANL 92-m tower. Contours are in meters relative to tower base.

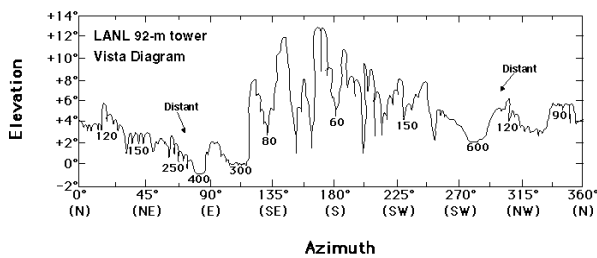


Figure 2. Vista diagram surrounding LANL 92-m tower base. Near and distant objects are represented by solid and dashed lines, respectively. Distances of near objects are given in meters.

The Rocky Flats Site is located approximately 25 km northwest of Denver, Colorado. The site is located on the eastern edge of a flat, geological bench known as Rocky Flats. This 8-km wide bench slopes slightly downward as it runs eastward from the eastern flank of the foothills of the Rocky Mountain Front Range, located to the west. Rolling terrain surrounds the bench in all other directions. Regional elevations range from 4,300 m ASL at the Continental Divide (33 km to the west) to about 1,600 m ASL in the South Platte River Valley (25 km to the southeast).

Unlike the LANL tower, the 61-m RF tower is situated over aerodynamically smooth terrain (see Fig. 3). Vegetation is limited to small trees near creeks that drain Rocky Flats. Several one- and two-story buildings are also located to the southeast. The RF tower site slopes about 2° downwards to the east-northeast. The tower base elevation is 1850 m ASL.

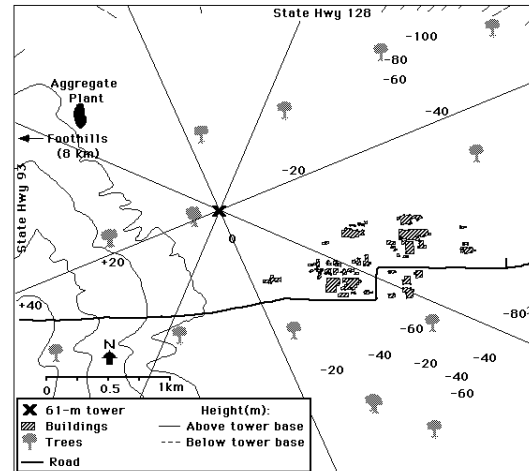


Figure 3. Contour map surrounding Rocky Flats 61-m tower. Contours are in meters relative to tower base.

High-quality instruments provided data at both sites. Wind direction and speed are routinely measured at LANL (12, 23, 46, and 92 m AGL) by low-threshold propeller anemometers and at RF (10, 25, and 60 m AGL) by low-threshold cup and vane systems. Vertical velocity is measured at both sites by vertical propellers using an extender and medium weight blades. Vertical velocities are routinely increased by 25% as suggested by the manufacturer (R.M. Young) in order to compensate for the non-cosine response of the instruments. Finally, precision pyranometers located near the respective towers at a height of 1.5 m AGL provided incoming solar radiation (insolation) data. Campbell Scientific dataloggers routinely sense all variables at 0.33 and 1 Hz rates at LANL and RF, respectively. Fifteen minute means and standard deviations are calculated at both sites. Finally, dataloggers at both sites use the same method recommended by Yamartino (EPA 1993) to calculate  $\sigma_\theta$ .

### 3. DATA ANALYSIS DESCRIPTION

Fifteen-minute averaged wind and insolation data were analyzed for the year of 1994 at both sites for eight directional sectors during near-neutral conditions. The large aerodynamic roughness at LANL precludes using a wind speed minimum of 5 or 6 m/s to produce an adequate sample of near-neutral cases for all directions. Therefore all cases with  $u > 3.5$  m/s and slight insolation ( $< 350$  W/m<sup>2</sup>) were assumed to be near-neutral. The annual dataset produced primarily D and some C and E P-G stability cases according to an objective Turner method suggested by Bowen and Pamp (1994). A higher threshold of 5 m/s and slight insolation were used at the smoother RF to determine near-neutral (D and a few C) stabilities.

Annual median wind speeds and turbulence coefficients were calculated in this study. Median values are better able to represent “typical” conditions than mean values since they give less weight to unusual or extreme data (e.g., very strong winds). Previous turbulence studies at LANL (Bowen *et al.* 1983) and RF (Bowen and Pamp 1994) also indicate skewed turbulence distributions during stable conditions. Therefore the use of median turbulence parameters allows the most reliable comparisons among various stabilities.

Dataloggers directly calculate  $\sigma_u$ ,  $\sigma_\theta$ , and  $\sigma_w$  at both sites. The following transform was used to convert from angle to speed (and vice versa):

$$\sigma_{\theta,\phi} = \frac{\sigma_{v,w}}{u} \quad (1)$$

Finally, “local” and “regional”  $z_o$  were determined from tower wind speed profiles and turbulence ( $\sigma_u$ ) values, respectively, at both sites. Best fit lines of  $u$  vs.  $\ln(z)$  were derived for each direction to determine a “local” roughness length  $(z_o)_p$ , while the following equation was used to determine a “regional” roughness length  $(z_o)_{tu}$  as suggested by Tieleman (1992) and others:

$$(z_o)_{tu} = \exp[\ln z - 1/(\sigma_u/u)]. \quad (2)$$

Eq. (2) is derived from the logarithmic wind profile equation and the widely-used approximation  $\sigma_u/u^* = 2.5$ , based on measurements over FSU terrain. “Regional” roughness lengths require values of  $\sigma_u$  (or  $\sigma_v$ ) and  $u$  at a single level. Presumably, they approximately equal  $(z_o)_p$  in FSU terrain.

## 4. RESULTS AND DISCUSSION

### 4.1 Profile- vs. turbulence-derived $z_o$

Annual median values of  $(z_o)_p$  and  $(z_o)_{tu}$ , calculated for eight directional sectors during near-neutral conditions at LANL and RF are shown in Figs. 4 and 5. Note that  $z_o$  values could not be calculated for the eastern sector at LANL since easterly winds rarely exceed 3.5 m/s. The local  $z_o$  values exceed the regional  $z_o$  values in all seven sectors. The largest difference in the  $z_o$  values occurs in the northwest sector where there is a long fetch without trees. Both  $z_o$  values are remarkably similar for all sectors considering the differences in upwind fetch. The systematic difference in  $z_o$  values merely indicates that use of  $(z_o)_p$  slightly overestimates horizontal turbulence values at the LANL site. In other words, horizontal turbulence has not fully adjusted to the local  $z_o$  except in the south sector.

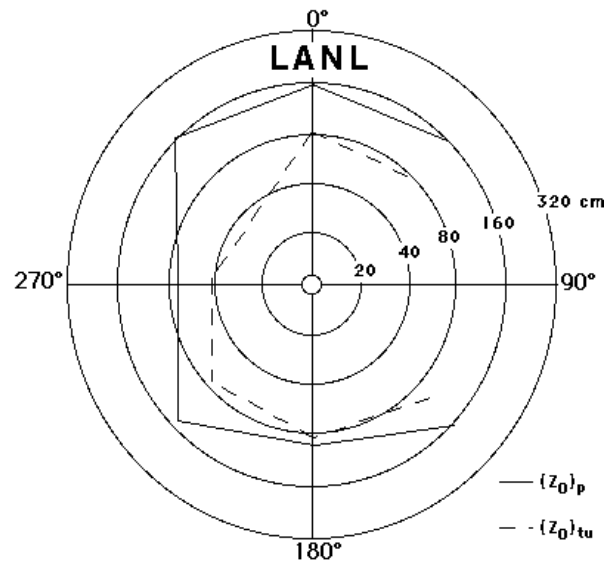


Figure 4. Polar diagram of roughness lengths at Los Alamos.

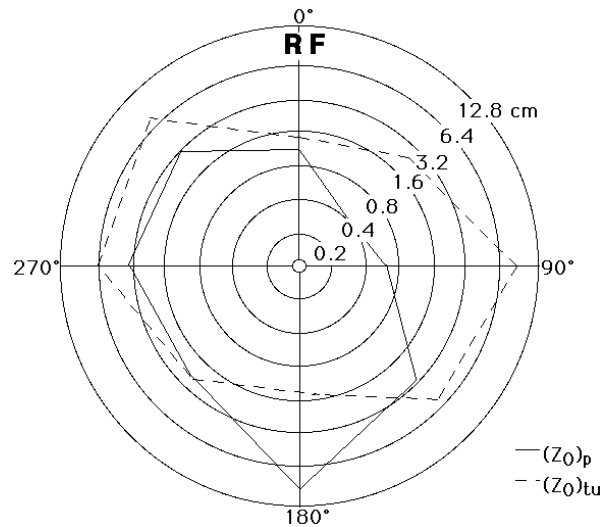


Figure 5. Polar diagram of roughness lengths at Rocky Flats.

The relationship of  $z_o$  values is reversed at the smoother RF site:  $(z_o)_{tu} > (z_o)_p$  in six of the eight sectors. This suggests that horizontal turbulence generated regionally (rolling terrain) generally exceeds the amount expected over FSU terrain. Note that  $(z_o)_{tu}$  [or  $\sigma_u$ ] increases toward the E and SE sectors, possibly because of numerous buildings. The somewhat higher  $(z_o)_{tu}$  values in the W and NW sectors may be a result of some enhanced turbulence generated by the Front Range.

## 4.2 Turbulence coefficient profiles

Profiles of median turbulence coefficients at LANL and RF are shown in Figs. 6 and 7, respectively. Note the values are averages over all sectors at each site. While turbulence values varied significantly by sector at both sites, the change with height was relatively uniform for all sectors.

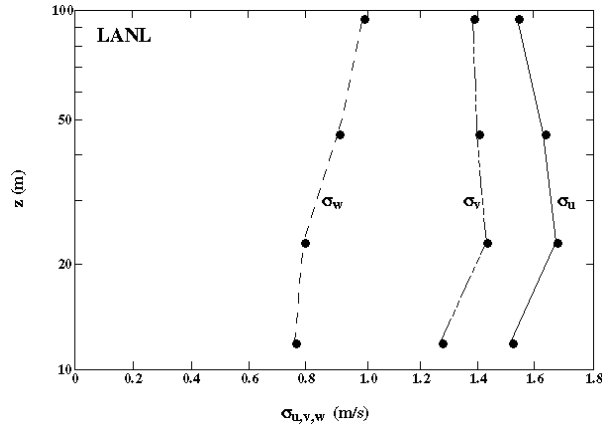


Figure 6. Profiles of median  $\sigma_u$ ,  $\sigma_v$ , and  $\sigma_w$  at Los Alamos during near-neutral conditions in 1994.

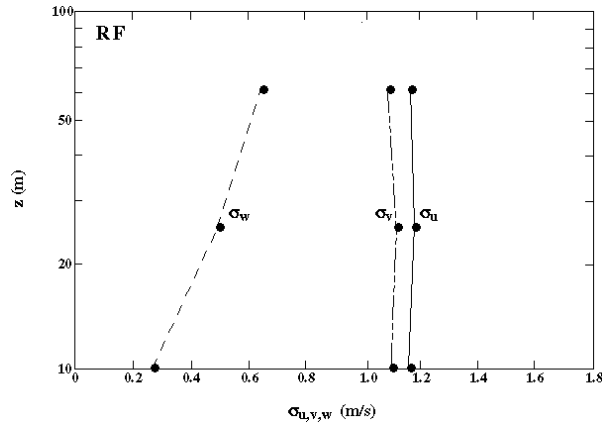


Figure 7. Profiles of median  $\sigma_u$ ,  $\sigma_v$ , and  $\sigma_w$  at Rocky Flats during near-neutral conditions in 1994.

The horizontal turbulence coefficients  $\sigma_u$  and  $\sigma_v$  increase about 13% from the 12- to 23-m level and then they slowly decrease with height at LANL. However the assumption of constant  $\sigma_u$  and  $\sigma_v$  with neutral surface layer height seems to be a fair assumption at LANL, even with locally inhomogeneous roughness elements. The variation of  $\sigma_w$ , however, is considerably larger; it increases by more than 30% with height. The ratio of  $\sigma_v/\sigma_u$  falls within 0.7 to 0.9, the range reported in the literature, and increases from 0.84 at 12 m to 0.90 at 92 m AGL. The ratio of  $\sigma_w/\sigma_u$  increases from 0.50 at 12 m to 0.65 at 92 m AGL,

which also agrees with widely-used experimental values (Panofsky and Dutton 1984).

The  $\sigma_u$  and  $\sigma_v$  values at RF are nearly constant with height (see Fig. 7). The ratio of  $\sigma_v/\sigma_u$  is somewhat larger at RF than LANL, averaging 0.94. However, the vertical turbulence ( $\sigma_w$ ) increases by a surprising factor of 2.5 from 10 to 60 m AGL. The ratio of  $\sigma_w/\sigma_u$  increases from 0.23 at 10 m to 0.55 at 60-m AGL. The 60-m ratio of  $\sigma_w/\sigma_u$  agrees closely with widely assumed values in the literature. An interesting result is that even though RF indicates a larger *percentage* increase with height, the *incremental*  $\sigma_w$  increase ( $\sim 0.2$  m/s) is similar between the 20- and 60-m heights at both sites.

The increase of  $\sigma_w$  with height in complex terrain may actually be a common occurrence during near-neutral stability. The idea that upstream terrain or obstacles can affect horizontal turbulence coefficients was first suggested by Panofsky *et al.* (1977) and verified experimentally by him and others. Since the terrain-induced eddies have large wavelengths, they require several kilometers of fetch to adjust. In contrast, Panofsky *et al.* (1977) and others have dismissed the effect of terrain features on vertical turbulence and assume that the higher frequency vertical turbulence quickly adjusts to “local” terrain.

The neglect of terrain-enhanced vertical turbulence has occurred because most experiments have taken place in homogeneous surroundings while  $\sigma_w$  profiles have typically been limited to about 25 m AGL or less (see Pasquill 1974). Furthermore, unlike  $\sigma_\theta$  and  $\sigma_u$ ,  $\sigma_w$  is not typically measured routinely by operational towers. A study by Beljaars *et al.* (1983) in a flat agricultural area (Cabauw tower) is the only description of increasing  $\sigma_w$  with height this author could find in the literature. This study indicates that  $\sigma_w$  and  $u_*$  increase 40% with non-uniform fetch and they remain unchanged with uniform fetch between 3.5 and 22.5 m AGL. The same study shows that  $\sigma_u$  and  $\sigma_v$  remain constant with height.

It appears that complex terrain and inhomogeneous fetch can enhance horizontal *and* vertical turbulence. The fact that  $\sigma_w$  is not enhanced near the surface during neutral conditions may simply mean that larger vertical eddies with sizes of about 100 m or so “aren’t felt” until  $z$  approaches the eddy size. The same situation occurs during unstable conditions when  $\sigma_w$  increases well into the boundary layer.

## 4.3 Implications for dispersion experiments

Angular turbulence statistics  $\sigma_\theta$  and  $\sigma_\phi$  are often used to estimate downwind dispersion or diffusivity coefficients ( $K_y$  and  $K_z$ ). Profiles of  $\sigma_\theta$  and  $\sigma_\phi$  were

calculated based on four different classes of  $(z_o)_{tu}$  at LANL and RF and are shown in Figs. 8 and 9. The four  $(z_o)_{tu}$  classes were determined by separating the sectors at each site into “rough” and “smooth” sectors. The  $\sigma_\theta$  profiles are relatively smooth and demonstrate a power-law decrease with height. This is not surprising since, at both sites,  $\sigma_u$  and  $\sigma_v$  are nearly constant with height while wind speed increases nearly logarithmically. Another interesting feature is that extensions of the profiles appear to converge between 100 and 200 m AGL (i.e., the surface layer depth).

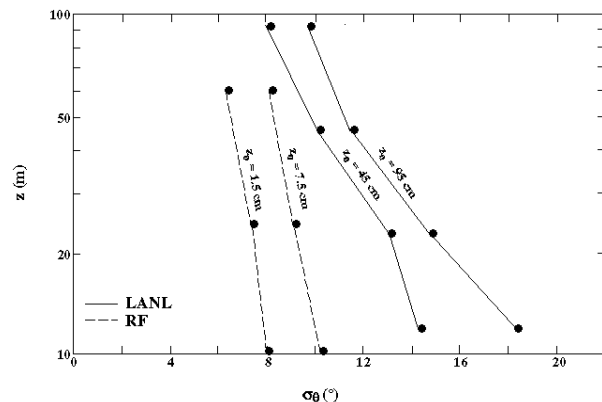


Figure 8. Near-neutral LANL and RF  $\sigma_\theta$  profiles during 1994. The LANL average  $(z_o)_{tu}$  for N, NE, SE, S, and SW sectors is 95 cm and 45 cm for the W and NW sectors. The RF average  $(z_o)_{tu}$  for E, SE, W, and NW sectors is 7.5 cm and 1.5 cm for the N, NE, S, and SW sectors.

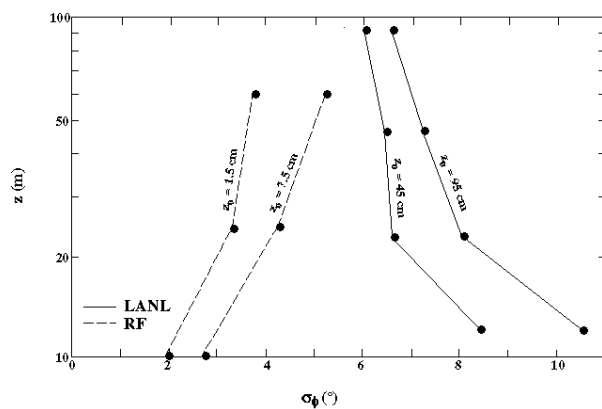


Figure 9. Same as Fig. 8 except for  $\sigma_\phi$ .

The  $\sigma_\phi$  profiles are more complicated and differ dramatically between the sites. The 10-m AGL  $\sigma_\phi$  values at RF are only 1/3 to 1/2 of the neutral values suggested by Irwin (1980) for terrain with  $z_o = 15$  cm. Even after adjusting  $\sigma_\phi$  for local  $z_o$ , the measured values are  $2^\circ$  below the midpoint of the recommended range for neutral stability. The  $\sigma_\phi$  nearly doubles from 10 to 60 m AGL at RF while it decreases by 33% from

12 to 92 m at LANL. Much of the decrease at LANL occurs below 23 m AGL, or tree height. Regional complex terrain appears to significantly increase  $\sigma_\phi$  above the very smooth local surface at RF and limit the decrease of  $\sigma_\phi$  above the 23-m height at LANL compared to  $\sigma_\theta$ .

The  $\sigma_w$  profiles suggest that models that use widely-used, experimentally derived, vertical turbulence values may not accurately describe vertical dispersion in the surface layer. First, the low-level values of  $\sigma_\phi$  at RF are about 50% lower than typically assumed over FSU terrain. Furthermore, if only the RF 10-m level  $\sigma_\phi$  were available, a dispersion modeler would most likely allow  $\sigma_\phi$  to slowly decrease with height. These differences alone could potentially cause under- or over-prediction of atmospheric concentrations for constant-level releases at 10- and 60-m levels, respectively. Errors could even be larger at RF for near-surface releases (e.g., heavy-gas releases) since  $\sigma_w$  appears to decrease below 10 m AGL. Estimation of  $\sigma_\phi$  with height at LANL based on the 12-m value could also cause significant underestimation of vertical dispersion with height.

## 5. SUMMARY AND CONCLUSIONS

A year of turbulence and wind speed profiles was analyzed in the near-neutral surface layer at two sites with complex terrain and contrasting values of local  $z_o$ . Results indicate that local  $z_o$  is greater (less) than the regional  $z_o$  at the rougher (smoother) tower site. Differences of the local and regional  $z_o$  values were as much as a factor of 2 at the rougher site and a factor of 10 at the smoother site for some sectors. This would suggest that  $(z_o)_p$  calculated from wind speed profiles can over- or underestimate horizontal turbulence depending upon the upwind regional fetch.

Horizontal turbulence intensities  $\sigma_u$  and  $\sigma_v$  are nearly constant with height up to 60 m AGL at the smooth RF site and vary 13% up to 92 m AGL at the rougher LANL site, primarily between the 12- and 23-m levels. The ratio of lateral to longitudinal turbulence intensity was generally near 0.9 at both sites. The vertical turbulence intensity  $\sigma_w$ , however, increases with height at both sites, especially at RF. The  $\sigma_w$  increases by a surprising factor of 2.5 from 10 to 60 m AGL at RF. Even though the percentage increase of  $\sigma_w$  is larger at RF, the incremental increase of 0.2 m/s between 20 and 60 m in AGL is similar at both sites and presumably a result of the regionally complex terrain. While the enhancement of horizontal turbulence by regional-scale terrain features is widely known, vertical turbulence is assumed to scale quickly to local terrain. It is proposed that  $\sigma_w$  is also intensified in complex terrain and normally increases with height in the neutral surface layer. The  $\sigma_w$  increases with height since

larger, vertically-oriented eddies are “felt” more above the surface.

Using measured surface layer turbulence in complex terrain may improve the accuracy of dispersion model estimates. Widely-used  $\sigma_w$  estimates can differ from measured values by a factor of two or more. Near-surface turbulence measurements suggest that the M-O similarity assumption of constant horizontal turbulence in complex terrain is valid. However, the influence of regional  $z_o$  must be accounted for when estimating  $\sigma_w$  profiles. Otherwise, additional errors of a factor of 2 or more may easily be introduced into predicted concentrations.

The effect of complex terrain on turbulence intensity profiles during stable and unstable conditions at these two sites will be studied in the future. In addition, other sites with measured  $\sigma_w$  profiles will be identified in order to further verify the apparent effect of regional terrain on turbulence. Profiles of  $\sigma_w$  up to several hundred m AGL should be analyzed to determine the height range in which intensification of  $\sigma_w$  occurs. Finally, the effect of increasing  $\sigma_w$  with height on surface layer dispersion will be analyzed by running the Atmospheric Release Advisory Capability (ARAC) 3-D atmospheric dispersion model (ADPIC) over complex terrain.

## 6. ACKNOWLEDGMENTS

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